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Enameled glass panels for solar thermal building envelopes

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Abstract

The paper presents a novel concept of solar thermal panel specifically intended for building integration, aiming at a higher architectural quality and at a reduction of installation costs. The panel consists of a low-emissivity enameled flat glass as solar absorber and a metallic heat exchanger, which are glued together by an adhesive layer. It features high design flexibility and can be used as roof or façade cladding in combination with common frames and profiles. We analyze the potential of the panel both as uncovered and covered collector by means of efficiency measurements on large-sized prototypes according to ISO 9806. Our results show that panels equipped with black enameled glass can achieve performance values competitive with those of commercial available products (uncovered panel: $\eta_0 = 0.75$, $b_1 = 8.05$ W/m²K, $b_2 = 1.64$ J/m³K, $b_u = 0.043$ s/m; covered panel: $\eta_0 = 0.74$, $a_1 = 4.26$ W/m²K, $a_2 = 0.013$ W/m²K²). As reported by our optical measurements on small samples, colored glass can exhibit solar absorptance up to 0.93, thus representing an aesthetically appealing alternative to black panels. For its implementation, system integration, operating conditions and design aspects have to be taken into consideration.

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Keywords: solar architecture; building integration; flat plate collector; glass; enamel; low-e coating

1. Introduction

Building integration has long been recognized as a promising approach for a more successful dissemination of solar thermal systems for domestic hot water and space heating.

An improved architectural and constructional quality of the installation can increase the acceptance among architects and end-users and at the same time reduce the system cost thanks to synergic effects. Up to now, however,

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building integration represents the exception in the realization of solar plants and is still far from becoming an established practice. The different motivations for that have been analyzed in detail in earlier as well as in more recent studies [1; 2]. The lack of suitable products, able to offer aesthetical quality and sufficient design freedom is identified as one of the decisive factors.

After current integration approaches the solar panel typically replaces part of the building envelope by adapting to the existing circumstances (type of construction, materials, surface finishes, colors, etc.). Many manufacturers offer their own solutions, with appropriate mounting kits, frames and covering strips. Some other solar companies have special products with modular design in their portfolio, which can be produced in a large variety of formats and sizes, thus ensuring architecturally more appealing installations [3; 4].

A second, less common approach consists in modifying the components of the building envelope themselves to enable the active use of solar energy. Examples can be found particularly in research works [5; 6; 7; 8] but also on the market [9]. This approach is technically more demanding and presupposes the definition of new scenarios in the development and marketing of the products as well as in the planning and realization of building projects, but it can open up new success chances for the solar assisted heat generation in buildings.

The paper presents a novel glass panel, which follows this second development principle and is conceived as solar thermally activated version of glazed components for façades and roofs.

Nomenclature

a_1	heat loss coefficient (covered collectors), [W/m²K]
a_2	temperature dependent heat loss coefficient, [W/m²K²]
a_{40}	heat loss coefficient at a temperature differential of 40 K between fluid and ambient air, [W/m²K]
b_1	heat loss coefficient (uncovered collectors), [W/m²K]
b_2	wind speed dependency of the heat loss coefficient, [J/m³K]
b_u	wind speed dependency of the zero heat loss efficiency, [s/m]
G	hemispherical solar irradiance in the collector plane, [W/m²]
G”	hemispherical net irradiance in the collector plane, [W/m²]
T_{Air}	air temperature, [°C]
T_{Fluid}	mean collector fluid temperature, [°C]
T_{Sky}	sky temperature, [°C]
α	solar absorptance, [-]
ε	thermal emittance, [-]
η	collector efficiency, [-]
η_0	zero heat loss efficiency, [-]
τ	solar transmittance, [-]

2. Concept, design and integration

The new solar panel results from the combination of a tempered glass pane with a heat exchanger: To ensure the mechanical and thermal coupling of the two components we are investigating different approaches, but focusing on adhesive bonding (s. Figure 1).

The glass pane takes over the static and aesthetical function in the compound, but is also responsible for the absorption of the incident solar radiation: Absorption can take place either in the bulk (colored glass) or in the underside of the pane (enameled glass). The wide range of geometries, sizes, colors, patterns or surface finishes enables an almost unlimited design freedom. This ensures optimum adaptation to the architecture of the specific building, which is not the case with common commercially available solar panels. Furthermore, the glass surface exhibits a perfect planarity not yet achievable by metallic absorbers, independently of the manufacturing technology used (laser or ultrasonic welding, gluing, etc.). The application of a low emissivity (low-e) coating on the front side of the glass pane can significantly reduce the heat losses by radiation and enhance the performance of the panel, in a similar way as with spectrally selective solar absorbers. For this purpose transparent conductive coatings based on metal oxides (for example indium, tin and zinc) represent the best suitable choice, as they exhibit lower optical losses and a much higher durability compared to silver coatings commonly in use for windows and glass architecture [10]. In our work, we implement indium tin oxide coatings (ITO), which were specifically developed for solar thermal applications in cooperation with the German company Euroglas during an already completed research project [11]. The separation of the two functions solar absorption (bulk or rear side) and thermal emission (front side) enables the manufacturing of selective glass panes with a predefined emittance in any color or design. This aspect furtherly distinguishes the novel glass panel from metallic solar absorbers [12].

In choosing the heat exchanger and the connection between glass pane and heat exchanger both conventional and new components can be used. Two essential requirements need to be fulfilled: On the one hand, the absorbed energy has to be effectively transferred from the low thermally conductive glass pane into the fluid. On the other, the long-term stability of the entire compound has to be ensured under the expected thermal and thermomechanical stresses during operation (maximum temperatures up to 120°C and 200°C in case of stagnation, for the uncovered and covered assembly respectively). For the heat exchanger different metallic designs have being tested, for the connection both dry and wet bonding processes. Hot lamination is taken into account as well, following a manufacturing approach commonly in use for photovoltaic modules and already proven also for photovoltaic-thermal collectors. For the adhesive layer, different materials have been investigated so far: acrylates, silicones, epoxy resins and modified, temperature resistant ethylene vinyl acetate films.

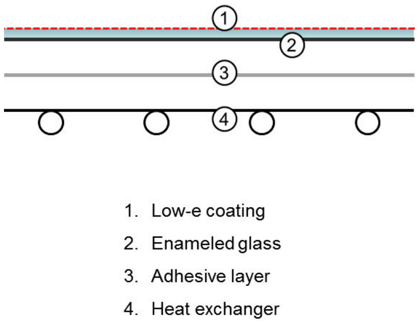


Fig. 1. Large-sized prototype (1800 x 1100 mm, links) and schematic design (right) of the novel solar glass panel.

The resulting solar panel can be directly integrated into the building envelope and be operated as uncovered collector or can be processed into a multiple insulating glass, in order to produce heat at higher temperatures and thus to extend its application range.

Multiple glazed panels can be manufactured with standard equipment for the production of insulating glass, with the difference that appropriate temperature-resistant sealing materials are to be used in this case. For our investigations special thermoplastic spacers produced by the German company Kömmerling Chemische Fabrik are implemented, which had been already successfully tested in previous R&D-projects [7; 11].

The panels can be integrated as single or multiple glazed units in different ways into the building envelope: As cladding in warm and cold façades or roofs as well as opaque glazing in windows or glass constructions (s. Figure 2). For the installation conventional profiles, frames and fixing systems for glazed components (clamps, fittings, adhesives, etc.) can be advantageously used.

As part of an ongoing research project in cooperation with industry partners, our work is specifically focused on rear-ventilated frameless glass facades.

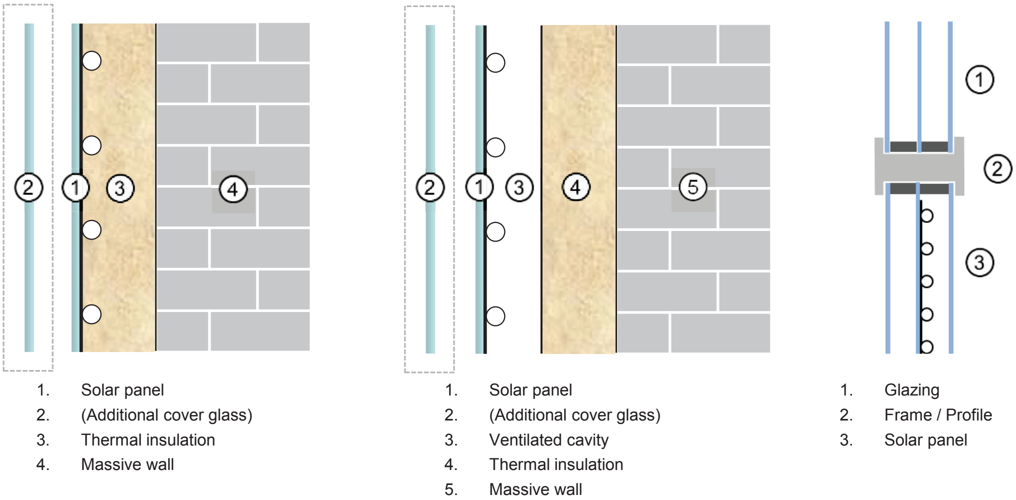


Fig. 2. Examples for the integration of the solar glass panel into the building envelope: As cladding in warm and cold façades (left, center) or as opaque glazing in windows or glass constructions (right).

3. Performance measurements on prototypes

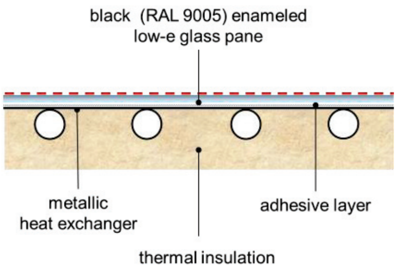
The feasibility of this concept has already been assessed in previous studies at ISFH [10]: For the first prototypes, commercially available selective glass panes (KGlass™ from Pilkington) were clamped on metallic black painted, laser welded solar absorbers. Despite the suboptimal assembly (optical losses due to the high solar reflection of the coating and to the air gap between the glass pane and the solar absorber), the achieved results could show the potential of the collector and helped identifying the required optimization steps. Based on this preliminary work, we have further developed the panel and manufactured prototypes with different designs. For the investigations documented in this paper, KGlass™ was replaced with a customized pane produced by the company Euroglas featuring full-surface opaque enamel on the underside and the selective ITO coating already mentioned in Section 2 on the front side. A composite heat exchanger consisting of copper tubes and aluminum thermally conductive sheets was attached to rear side of the glass pane with a dry bonding process.

This solar "glass absorber" exhibits very good optical properties: In a black enamel finish (color: RAL 9005) we reported a solar absorptance of 0.94 ± 0.01. The thermal emittance varies between 0:20 and 0.30 ± 0.02, depending on the coating design, but regardless of the enamel color. The measurements in the solar spectral range were carried out on large-sized samples with a commercial double-beam spectrometer equipped with an integrating sphere (Cary 5000 from Varian/Agilent). The measurements in the infrared spectral range were carried out on small samples with a commercial Fourier transform infrared spectrometer (Equinox 55 from Bruker) and validated on large-sized prototypes by means of thermographic methods.

The internal heat transfer coefficient U_{int}, describing the capability of the solar absorber to transfer heat from the absorber plate (in our case the glass pane) to the fluid, varies considerably depending on the design of the heat exchanger (material and geometry) and on the nature of the adhesive bond (thickness, application area and thermal conductivity). Up to now we have reported values between 15 and 60 W/m²K.

Figure 3 shows the efficiency curves of an uncovered prototype panel and commercially available products at different wind speeds. The performance data of the panel were determined by means of outdoor measurements at ISFH in accordance with the standard ISO 9806 and are summed up in Table 1.

Thanks to the design and manufacturing optimization undertaken, the conversion factor could be increased by more than 3 points with respect to the work documented in [10], up to 0.75. According to the current development status a value of about 0.80 is considered to be technically feasible. Despite the comparable solar absorptance, the conversion factor of the panel still remains significantly below that of the referenced collectors, which exhibit a very high internal heat transfer due to of their special design. The results prove the other hand the performance of the panel at higher operating temperatures, as a consequence of its low heat loss coefficient (low-e coating and back insulation).



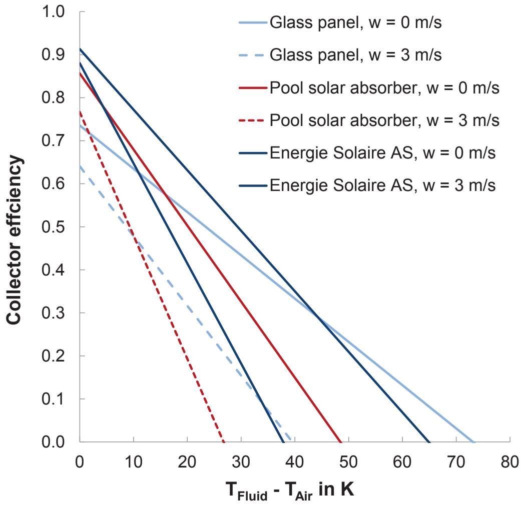


Fig. 3. Schematic design (left) and measured efficiency curves of an uncovered glass panel prototype and commercial products (right). The correspondent collector parameters are reported in Table 1. To enable the comparison between selective and non-selective collectors, the curves refer to the hemispherical solar irradiance G and not to the net irradiance G" (boundary conditions: G = 800 W/ m²; T_{Air} = 25 ° C; T_{Sky} = 16 ° C; collector slope = 45°).

Table 1. Performance data of the uncovered collectors used for the comparison, referred to the aperture area.

Collector type	η_0 [-]	b_u [s/m]	b_1 [W/m²K]	b_2 [J/m³K]
Kollektor AS, Energie Solaire [14]	0.93	0.012	11.26	2.45
Swimming pool absorber, Bomin Solar [13]	0.91	0.035	14.14	2.93
Solar glass panel (ISFH measurement)	0.75	0.043	8.05	1.64

The energetic behavior of the panel is more clearly represented in Figure 4: Here the calculated annual thermal energy output based on the collector characteristics and on predefined boundary conditions is displayed for different inlet temperatures. Compared to the high-performance product Kollektor AS from the Swiss company Energie Solaire, the glass panel shows about 20% lower energy gains, but a similar temperature dependency. Compared to the swimming pool absorber, the panel achieves similar results at an inlet temperature of 10 °C, but reports significantly higher gains at 20 °C (+ 20%) and 30 °C (+ 55%).

For building integration, panels in different colors or patterns can represent an aesthetically appealing solution. To investigate their potential, we carried out optical measurements on small, commercially available enameled glass samples. The tests, which were carried out with the equipment already mentioned in this section, reported very promising results, featuring solar absorptance values ranging between 0.73 and 0.93. Lower solar absorptance corresponds to a reduction of collector efficiency, which can to some extent be compensated by an increase of the collector area. The effectiveness of this compensation is strongly dependent not only on the specific panel properties, but also on the specific heat supply system and on the operating conditions. The economic aspects (energy savings vs. additional costs for solar thermally activated panels) should also be taken into consideration in the planning. These crucial topics are currently addressed by running system simulation studies.

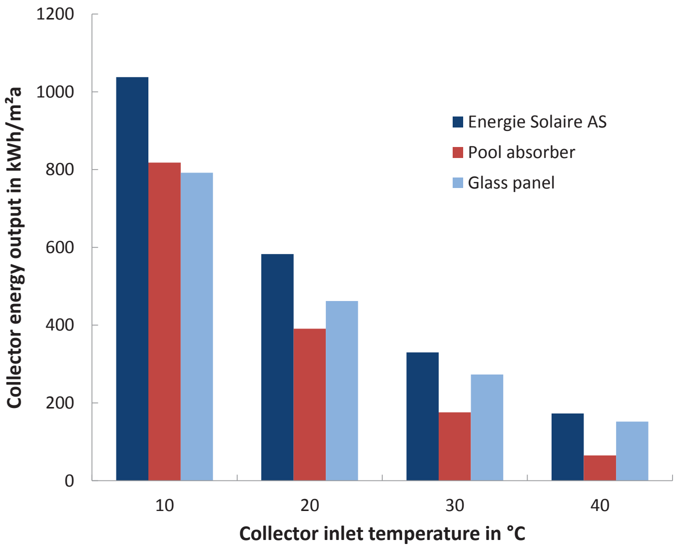


Fig. 4. Annual thermal energy output of an uncovered flat plate collector based on the new glass panel, compared to those of commercial products, at different collector inlet temperatures. The simulations were performed with the software TRNSYS on the basis of measured collector characteristics, as reported in Table 1 (weather data: Meteonorm, Zürich; collector slope: 45 °).

Figure 5 compares the efficiency curves of a covered prototype and a common, spectrally selective flat plate collector. The prototype features a low-iron glass cover (solar transmittance 0.90 ± 0.01) and an argon-filled gap between the panes. For the measurement, the panel was mounted in a customized case with 30 mm back insulation. The collector efficiency parameters were determined at ISFH by means of indoor and outdoor tests according to ISO 9806 and are summed up in Table 2.

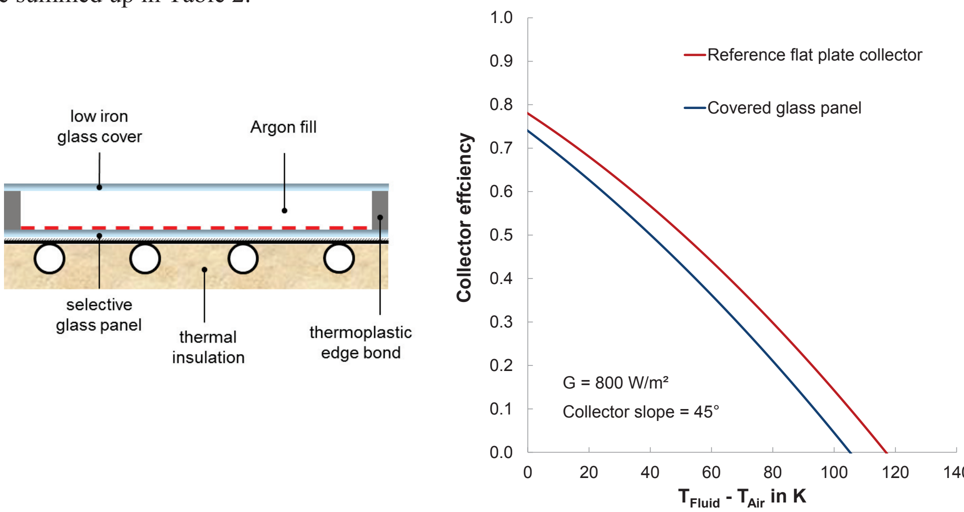


Fig. 5. Schematic design (left) and thermal efficiency curves of a covered flat plate collector based on the new glass absorber and a commercial product (right). The glazing unit exhibits a low-iron glass cover and is filled with argon, the collector is provided with 30 mm back insulation.

The results attest even in this case the potential of the new solar panel: The heat loss coefficient is in the range of standard flat-plate collectors, the lower conversion factor can be explained by the previously mentioned suboptimal thermal coupling between the glass pane and the heat exchanger, which can be enhanced through constructive improvements.

Table 2. Performance data of the covered collectors used for the comparison, referred to the aperture area.

Collector type	η_0 [-]	a_1 [W/m²K]	a_2 [W/m²K²]	a_{40} [W/m²K]
Reference flat plate collector [15]	0.78	3.70	0.014	4.26
Solar glass panel (ISFH measurement)	0.74	4.26	0.013	4.78

4. Conclusion and outlook

The paper presents a new concept of solar thermal panel, which combines an absorbing glass pane with a rear-mounted heat exchanger. Due to the high design freedom resulting from this unusual combination, the panel offers great potential for architectural integration into the building envelope, where it can be used as cladding or opaque glazing. Performance measurements on uncovered and covered, large-sized prototypes reported promising results. Current activities are focused on the optimization of the panel design: Our work aims not only at increasing the energy performance, but especially at ensuring the long-term reliability. The main chaallenge is the identification of an appropriate solution for the heat exchanger and for the adhesive bond to the glass pane. At a system level, simulation studies are in progress to analyze the suitability of the panel as heat source in combination with different heat supply concepts, depending on the building and panel design (uncovered/covered assembly and color).

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